Semiconductor photosensors for Cherenkov telescopes

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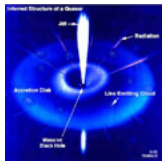
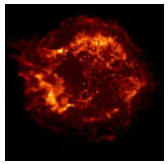
What do Cherenkov telescopes measure?

Some cosmic sources emit photons in the Very High Energy range:


AGN

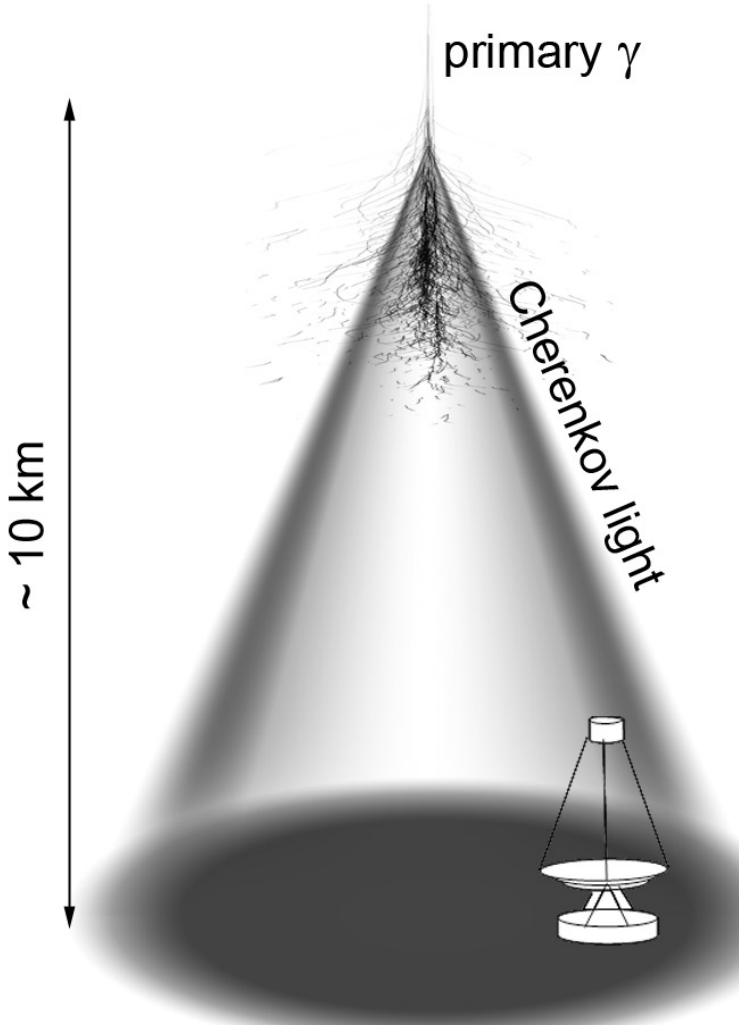

SNR


GRB


Pulsars

These photons are measured indirectly:

- Primary γ induce air shower
- Secondary particles emit Cherenkov light...
- ...which is detected by Imaging Atmospheric Cherenkov Telescopes (IACT)



...but you have already heard that in the previous talks...

What are the requirements to the camera?

Sensitivity: very few photons, eg. for $E_\gamma \approx 1\ TeV$: 100 photons/m^2 (300-600 nm, 2200 m a.s.l.).

Speed: very short flashes of a few nanoseconds.

Ruggedness: operation under outdoor conditions (high night sky background [$> 2 \cdot 10^{12}$ (m^2 s sr)$^{-1}$] and temperature variations).

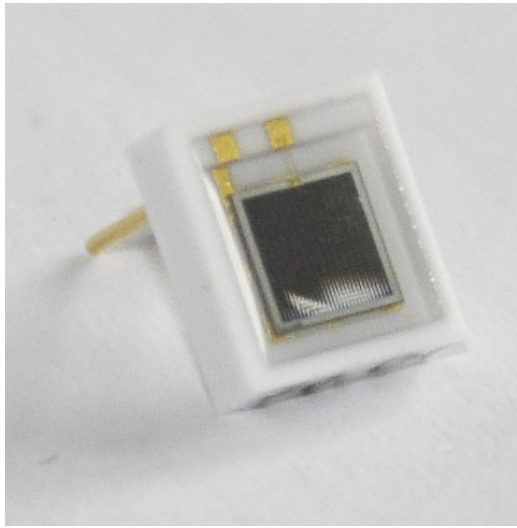
Ease of use: homogeneity, accidental triggers...

Today's IACTs: cameras based on photomultiplier tubes.

What are the advantages of semiconductor photosensors?

Compared to the commonly used photomultiplier tubes, photosensors based on semiconductors

- are very compact in size, low weight, mechanically stable
- are tolerant to bright light
- are insensitive to magnetic field
- do not need very high voltages



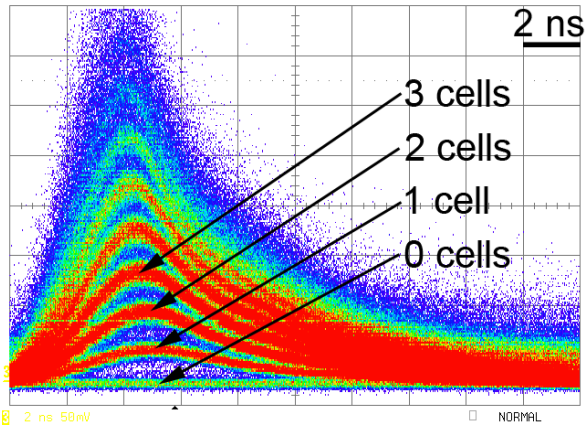
What types exist?

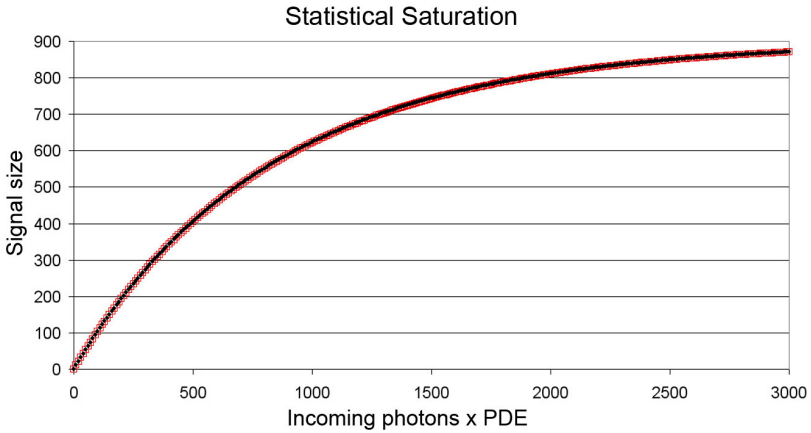
- PIN diode: very high quantum efficiency (80-90 %), but only gain 1
- Avalanche Photodiode: similar QE, gain typically 50-1000, but high excess noise factor
- Geiger-mode APD: higher gain and better noise characteristics, but has its own problems...
- (and some more...)

General properties of G-APDs

Geiger-mode Avalanche Photodetectors (G-APDs or SiPM, MPPC, PPD...)

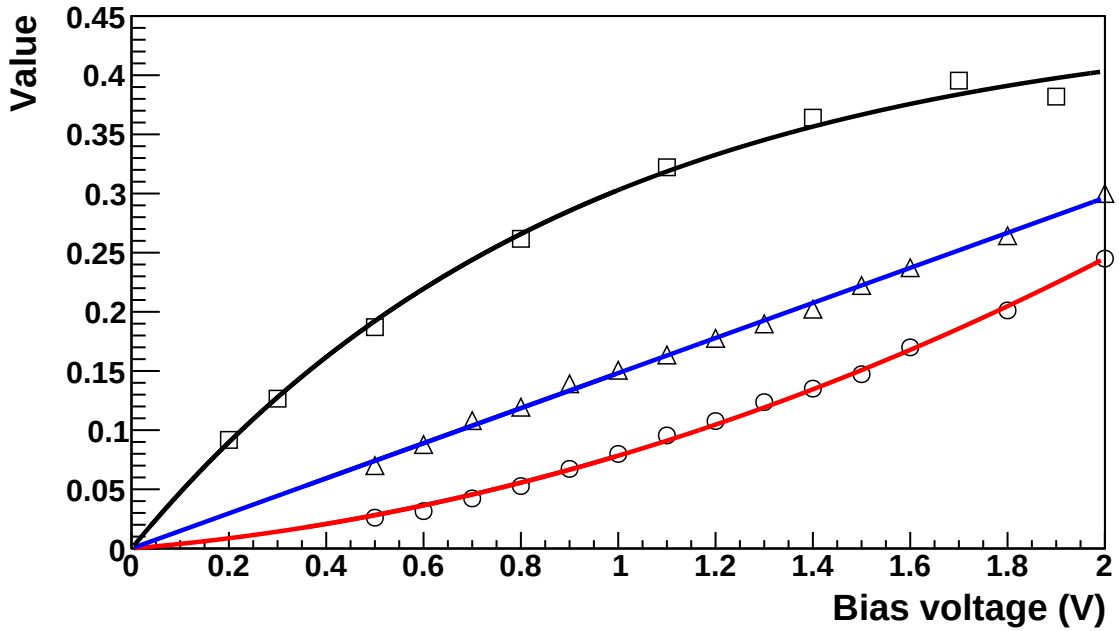
- Divided into a matrix of cells, 30-70 % active area
- Each cell can detect single photons → statistical saturation
- Crosstalk between cells possible
- Difficult analysis (saturation, crosstalk, afterpulses)
- Strong dependence on the so-called
  overvoltage = bias voltage - breakdown voltage
- The breakdown voltage is temperature dependent.





Voltage (temperature) dependencies

Light pulses of constant height: the signal of the G-APD depends on several parameters varying with the so-called overvoltage $V = V_{op} - V_{bd}$:



Photon detection eff.

Probability of a photon to trigger a G-APD cell

$p_1 \cdot (1 - e^{-V/p_2})$

Gain (scaled)

Charge released per triggered cell [in elementary charges]

Parametrization

$p_3 \cdot V$

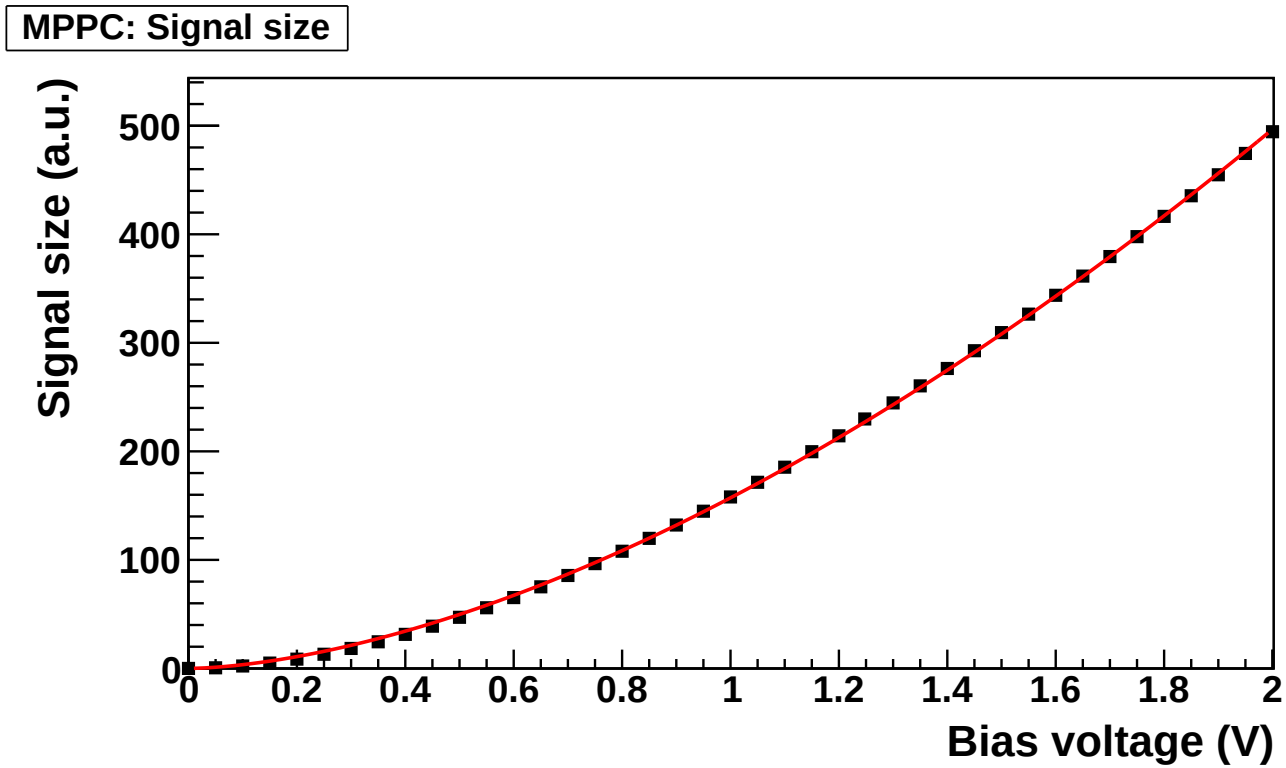
Crosstalk probability

Probability of a triggered cell to trigger another cell

$p_4 \cdot V^2 + p_5 \cdot V$

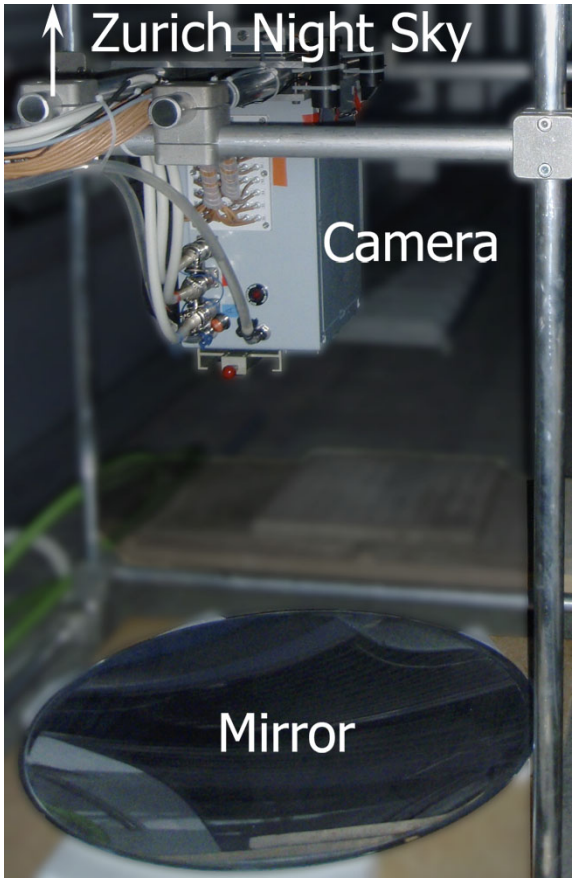
Total dependence on the overvoltage (temperature)

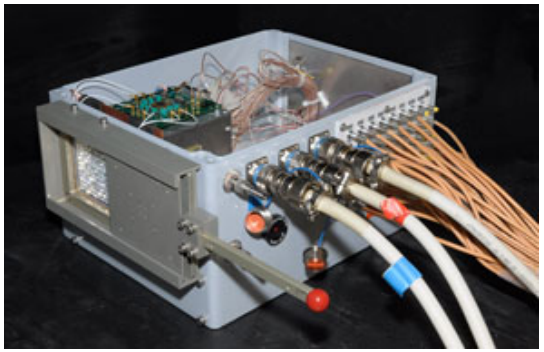
$\Rightarrow$ The total dependence on $V = V_{op} - V_{bd}$ is non-linear.
Hamamatsu S10362-33-050C: approximately proportional to $V^{1.66}$.

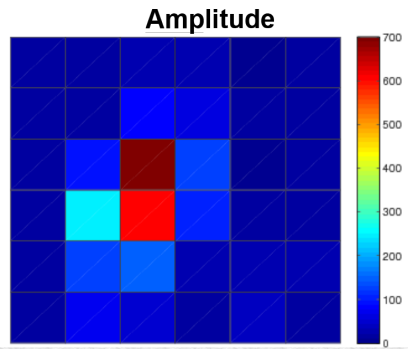


V_{bd} is temperature dependent.
$\Rightarrow$ The response of G-APDs is temperature dependent.

The First G-APD Cherenkov Telescope (FACT) Project: Prototype measurements







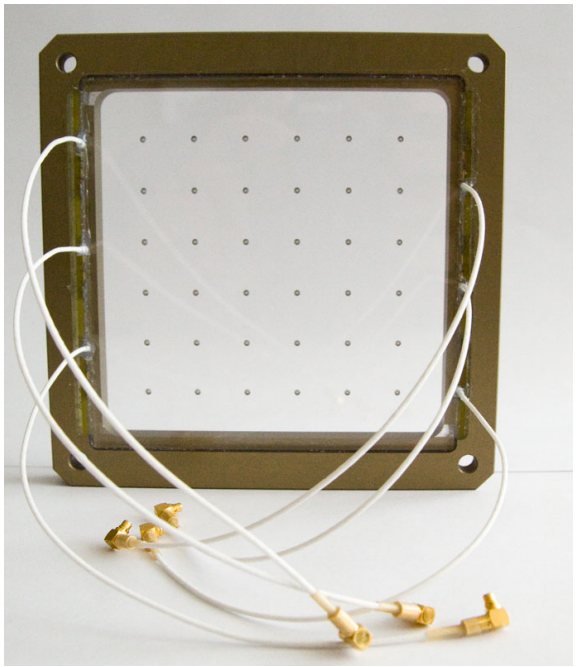
- Prototype module with 144 G-APDs in groups of 4 (total 36 pixel)
- Setup with a small mirror ($f = 80\,\text{cm}$, 1° field of view per pixel) on the roof of ETH Zurich
- First air showers measured

Controlling temperature variations: the feedback system

Outdoor conditions: temperature variations change the camera properties.

Temperature $\rightarrow$ breakdown voltage $\rightarrow$ overvoltage

$\Rightarrow$ Changing photon detection efficiency, crosstalk probability, gain



Feedback system:

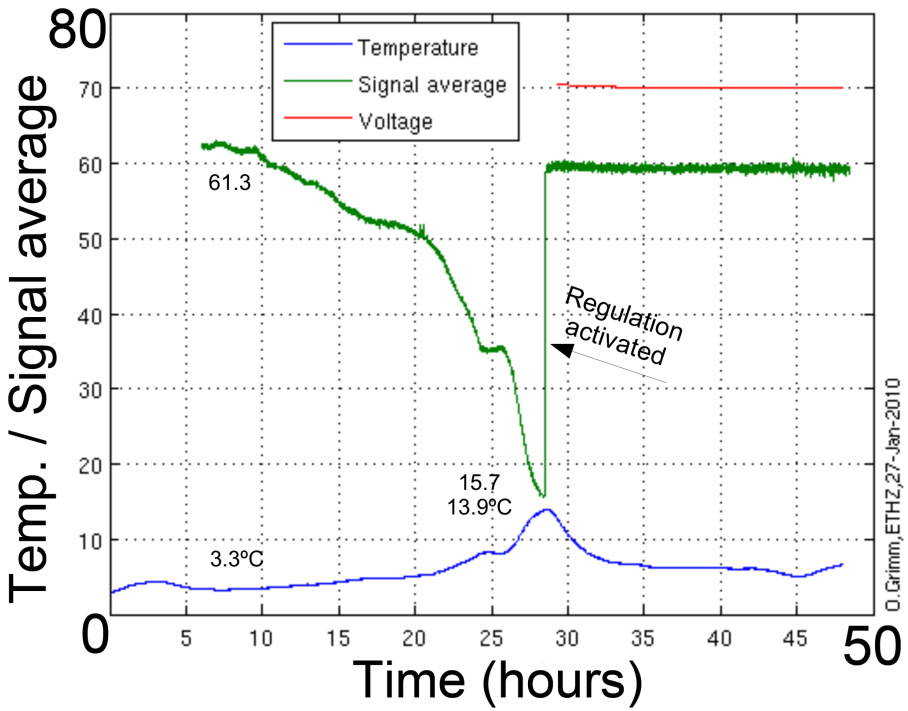
- Temperature stabilized LEDs in the entry window
- Short pulses
- Pulse reconstruction
- Voltage adjustment towards a target value

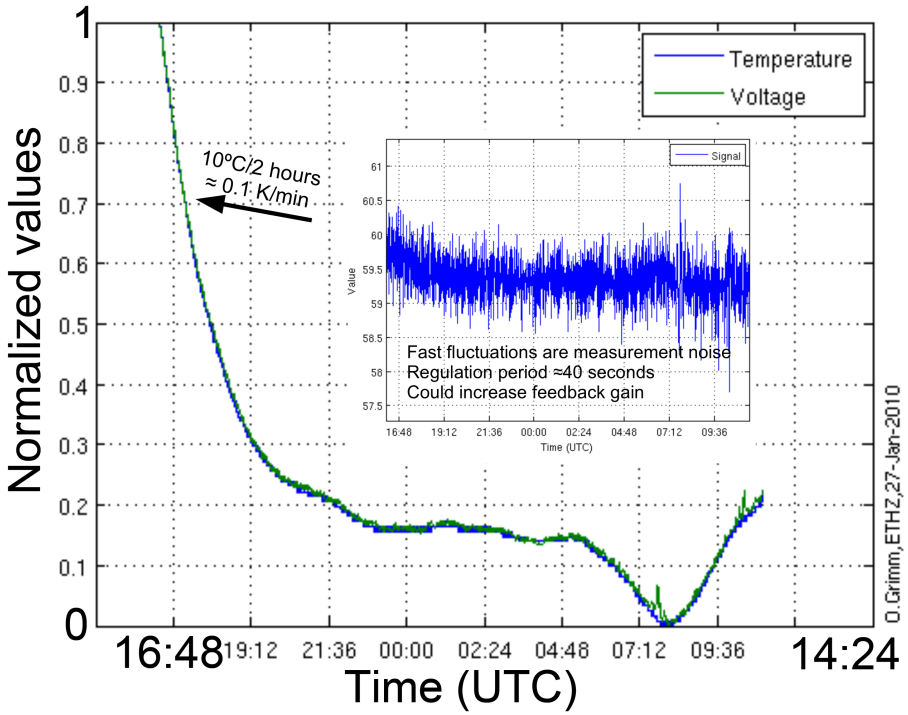
Feedback system test

Long-time measurement: January 20-22 2010.

First phase: feedback system deactivated, temperature change 10.6 K

Second phase: feedback system running, temperature change 7.6 K





⇒ Signal size stable within ≈ 0.5%.

Without feedback system: variations by more than a factor of 2.

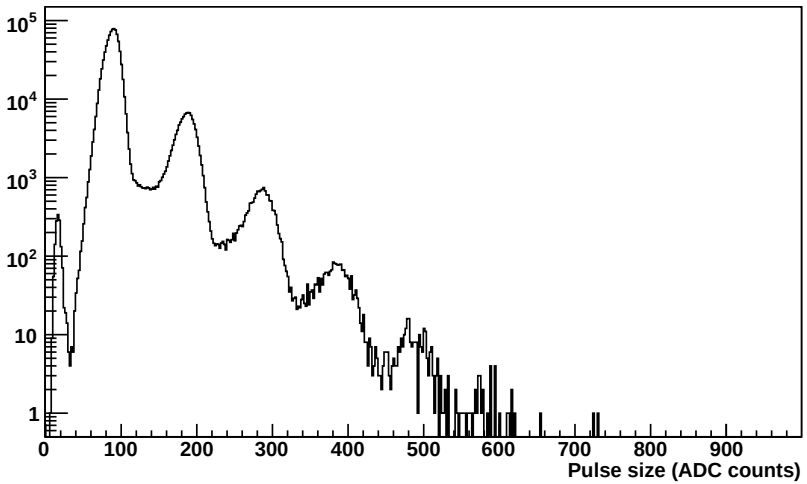
Summary

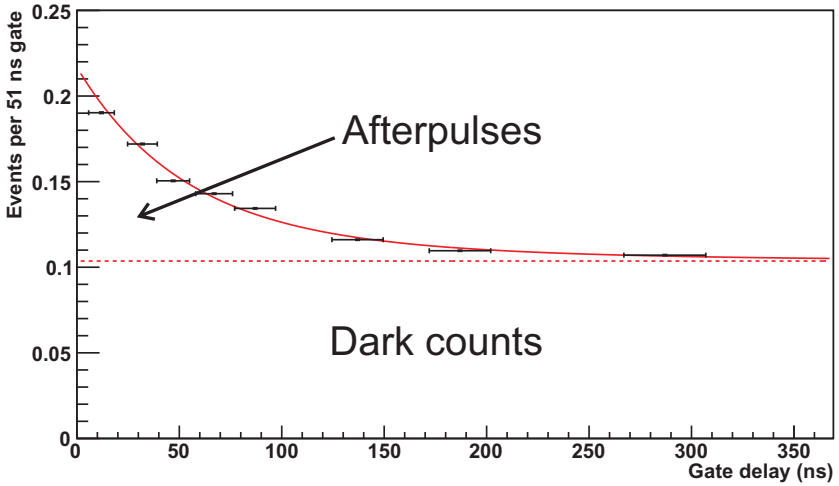
- A prototype module consisting of 144 G-APDs successfully tested and in operation since summer 2009
- First air shower pictures with a camera based on G-APDs
- Feedback system to correct for changes in the ambient temperature: gain stability $\approx 0.5\%$.
- Full-sized camera under construction

Backup slides

Afterpulses

The delayed release of carriers trapped during a breakdown in a cell can trigger the cell again.





Spectrum:

Measured spectrum of dark counts and afterpulses (crosstalk 13%).

Timing:

Number of pulses per gate for variable delays after an initial pulse. The number of pulses decreases exponentially to the level of dark counts.

$\Rightarrow$ Afterpulses are not a problem for the trigger.